 ARO 13470.2-GSX

ARO

RELATION OF INFRARED DOPPLER LIDAR TO REMOTE WIND MEASUREMENTS IN THE TURBULENT ATMOSPHERE.

FINAL REP[redacted]RT. 1 Feb 76 - 31 Jan 78

R. L./SCHWIESOW [redacted] R. F./CALFEE

31 Mar[redacted]78

12p.

U.S. Army Research Office

Contract Number ARO-9-76

National Oceanic & Atmospheric Administration
Wave Propagation Laboratory, R45X3
Boulder, Colorado 80302

APPROVED FOR PUBLIC RELEASE.
DISTRIBUTION UNLIMITED.

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARO 9-76	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) RELATION OF INFRARED DOPPLER LIDAR TO REMOTE WIND MEASUREMENTS IN THE TURBULENT ATMOSPHERE		5. TYPE OF REPORT & PERIOD COVERED Final Report 1 Feb 76 to 31 Jan 78
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. L. Schwiesow and R. F. Calfee		8. CONTRACT OR GRANT NUMBER(s) ARO 9-76
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Oceanic & Atmospheric Administration Wave Propagation Laboratory, R45X3 Boulder, Colorado 80302		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE 31 March 1978
		13. NUMBER OF PAGES 8
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18. SUPPLEMENTARY NOTES

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lidar
Wind Measurement
Doppler
Infrared
Turbulence

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The performance of a coherent Doppler lidar is affected by the atmosphere. Refractive index inhomogeneities limit the effective aperture of our system to 15.5 cm $\pm$ 4% on the average for a 2.6 km horizontal path 2 m above the surface under daytime conditions. Effective aperture scales as range to the -3/5 power. A differential Doppler technique can measure the wind vector in a single atmospheric volume with three (or more) closely-spaced beams. This method works even when the distribution of velocities in the volume is wider than
next page

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

than the velocity separation from beam angle differences. The structure function for backscatter and wind inhomogeneities scales approximately as $r^{2/3}$ between the minimum detectable scale in our experiment and an outer scale of 100 to 500 m, depending on atmospheric condition.

r to the 2/3 power

FINAL REPORT ON CONTRACT NUMBER ARO 9-76

1 February 1976 to 31 January 1978

RELATION OF INFRARED DOPPLER LIDAR TO REMOTE WIND MEASUREMENTS IN THE TURBULENT ATMOSPHERE

The performance of a coherent Doppler lidar is affected by the atmosphere. Refractive index inhomogeneities limit the effective aperture of our system to 15.5 cm ± 4% on the average for a 2.6 km horizontal path 2 m above the surface under daytime conditions. Effective aperture scales as range to the -3/5 power. A differential Doppler technique can measure the wind vector in a single atmospheric volume with three (or more) closely-spaced beams. This method works even when the distribution of velocities in the volume is wider than the velocity separation from beam angle differences. The structure function for backscatter and wind inhomogeneities scales approximately as $r^{2/3}$ between the minimum detectable scale in our experiment and an outer scale of 100 to 500 m, depending on atmospheric condition.

INTRODUCTION AND SUMMARY

In this report, we consider three aspects of infrared Doppler lidar performance in the atmosphere. Doppler lidars can be used to measure the component of the wind along the lidar line of sight. This measurement is made by measuring the velocity of small, naturally-occurring aerosols that serve as tracers of the ambient wind field. Aerosols are detected by the light backscattered from a laser source.

Wind measurements in regions of space remote from the lidar apparatus are useful in a number of applications. For example, the wind profile with height, or along a missile trajectory, can provide information to improve trajectory accuracy. Safe, close air support is aided by a knowledge of boundary layer winds. The transport and diffusion of airborne materials is controlled to a large extent by atmospheric flow.

Although the potential uses of Doppler lidar are fairly clear, performance of the systems is less certain. We have restricted our study to some performance aspects of an infrared, fully coherent Doppler lidar technique. Our observations can be summarized in three areas:

1) Temporal and spatial fluctuations in backscatter intensity and in velocity limit the usefulness of any azimuth-diversity technique used to obtain more than one component of the velocity.

2) A differential Doppler method for measuring the three components of velocity at a single region of space has been successfully demonstrated.

3) Refractive index fluctuations in the daytime boundary layer permitted an effective aperture of 15.5 cm $\pm$ 4%, on the average, for the apparatus and conditions examined in this project.

This report does not present technical details of the work performed because such information is covered in the papers that have appeared in or have been submitted to journals.

THE PROBLEMS STUDIED

1) Temporal and Spatial Structure Functions

The problem for this part of the project was to determine the time and space variation of backscatter intensity and the line-of-sight velocity component for representative meteorological conditions. Of particular interest was the space scale (determined from the time scale and velocity information) of the atmospheric inhomogeneities.

2) Differential Doppler Technique Exploration

In this part of the project, we intended to analyze the feasibility and suggest design parameters for a system to measure velocity components perpendicular to the nominal lidar axis. This procedure would allow determination of all three components of atmospheric velocity at a single point in space.

3) Atmospheric Effects on Lidar Coherence

The problem addressed in this area was to determine experimentally the effective telescope diameter for coherent processing under a range of meteorological conditions and path lengths. Auxiliary data considered was to include C_n^2 in the visible and surface temperature and humidity.

In summary, the research intended to develop basic information on the effects of the atmosphere on infrared Doppler lidar in the areas of atmospheric inhomogeneities in the aerosol and wind fields, atmospheric effects on the differential Doppler approach, and atmospheric limitations

on coherent Doppler processing. These studies were designed to be primarily experimental and analytical in nature in order to relate the performance of actual Doppler lidars to the real atmosphere.

SUMMARY OF RESULTS

1) Temporal and Spatial Structure Functions

The aerosol backscatter coefficient fluctuates in time and space. At 10.6 μm wavelength, backscatter changes occur in response to the changes in number density of large aerosols (> 2 μm radius). The spatial structure function is obtained from the intensities at distances x and x+r in the form

$$D(r) = [I(x) - I(x+r)]^2.$$

These fluctuations approximately follow an $r^{2/3}$ power law from r = 10 m to a saturation limit at approximately 300 m under average daytime conditions and 100 m under nighttime conditions. The distribution function for percent of time at a given backscatter value vs. the backscatter value shows that large values of backscatter occur only infrequently. The most probable backscatter is approximately 25% to 30% of the difference between minimum and maximum values above the minimum observed backscatter.

Fluctuations in velocity behave in a similar fashion to backscatter fluctuations. Time series of a single component of the daytime boundary layer wind show structure functions increasing to a scale of 300 to 500 m and then continuing approximately constant to the scale limit of the experiment. The technical papers listed below should be consulted for details of the experimental procedure and results.

2) Differential Doppler Technique Exploration

A measurement of the velocity components along two different lines-of-sight intersecting in a common atmospheric volume allows one to determine the vector velocity in the plane of the beams. The Doppler lidar beams must normally be sufficiently separated in angle so that the velocity components along each beam are well resolved for a velocity transverse to the beam bisector. Beam intersection angles of 90° would be ideal. Even for much more closely-spaced beams, a practical multibeam lidar is a bulky device when ranges of 30 m to a few kilometers are contemplated. The aerosols in a typical lidar sensing volume are distributed in velocity, thus giving a fundamental width to the Doppler velocity spectrum and providing a lower limit on the minimum interbeam angle for separate velocity resolution.

We have shown how it is possible to obtain the vector velocity from a velocity-distributed target with beam separation angles of 6 mrad, even though velocity components along such closely-spaced beams are not resolvably different. The technique relies on the fact that each beam is sensing the same atmospheric volume. If returns from the beams are mixed before a velocity signal is extracted, it is then possible to determine the velocity component transverse to the beam bisector. A beam separation of 6 mrad is not a fundamental limitation, but represents the limit of our initial demonstration. Three or more beams (used simultaneously or in a time-shared mode) allow all three components of the wind to be obtained at a single point.

The important point is that we have demonstrated how it is possible to use a Doppler lidar to measure the wind vector in a single lidar resolution

volume with a system that uses closely-spaced multiple beams. Although the geometry of our coherent lidar approach is similar to fringe techniques, the journal article clarifies significant differences between the two approaches.

3) Atmospheric Effects on Lidar Coherence

The lidar signal from an atmospheric scattering volume must be phase-coherent across the receiving telescope in order to mix efficiently with the local oscillator in a homodyne or heterodyne Doppler system. The atmosphere reduces the size of the coherent aperture because of inhomogeneities in refractive index at 10.6 μm for our lidar.

For a horizontal path 2 m above the surface, we found an effective aperture diameter of 15.5 cm ± 4% from an average of 61 daytime experiments over a 2.6 km range. The signal through a real aperture of the effective diameter is within 3 db of the maximum coherent signal available through any aperture. The effective aperture scales with lidar range to the -3/5 power, as expected from theory. Direct atmospheric attenuation in the clear atmosphere has a negligible effect on signal strength compared to atmospheric decohering effects when the aperture is as large as the effective diameter or larger.

POTENTIAL IMPACT ON REMOTE WIND MEASUREMENT TECHNOLOGY

The turbulent boundary layer limits the performance of a coherent Doppler lidar operating at 10.6 μm wavelength. Atmospheric refractive

index inhomogeneities limit the effective aperture of a system. This limits the achievable signal-to-noise or range of a practical lidar. Infrared attenuation measurements are best made with an incoherent setup to avoid masking from coherence effects. We intend to make any future systems with a 20 cm or less telescope aperture rather than the 30 cm now used.

The coherent differential Doppler approach allows measurement of three components of velocity in a single volume. This technique gives a significant increase in accuracy and reduction in scanning complexity over multiple-azimuth techniques.

Atmospheric velocity fields are generally inhomogeneous. Azimuth scanning methods for obtaining the vector wind are inherently limited in spatial resolution to the scanning volume. They can resolve time changes no faster than the order of the maximum dimension of the scanning volume divided by the mean wind.

The structure function for backscatter at 10.6 μm shows that at low signal-to-noise ratios there will be occasional signal dropout. Dropout can be determined from the structure function for a particular environment and the signal threshold for a particular system.

PUBLICATIONS

Three articles resulted from this project.

"Temporal- and spatial-frequency spectra for atmospheric aerosols," M. J. Post and R. L. Schwiesow, in Atmospheric Aerosols, NASA report NASA CP-2004, December, 1976, TuC9-1 to 4.

"Coherent differential Doppler measurements of transverse velocity at a remote point," R. L. Schwiesow, R. E. Cupp, M. J. Post, and R. F. Calfee, Applied Optics 16, 1145-1150 (1977).

"Atmospheric refractive effects on coherent lidar performance at 10.6 μm," R. L. Schwiesow and R. F. Calfee, in review.

Two other articles are closely related to this project, but not directly supported by it.

"A comparison of anemometer- and lidar-sensed wind velocity data," M. J. Post, R. L. Schwiesow, R. E. Cupp, D. A. Haugen, and J. T. Newman, Journal of Applied Meteorology 17, (1978).

"Experimental measurements of atmospheric aerosol inhomogeneities," M. J. Post, Optics Letters 2, (1978).

SCIENTIFIC PERSONNEL INVOLVED

R. L. Schwiesow

R. F. Calfee

M. J. Post

R. E. Cupp